

# Tuning the scattering length with an optically induced Feshbach resonance

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We demonstrate optical tuning of the scattering length in a Bose-Einstein condensate as predicted by Fedichev *et al.* [Phys. Rev. Lett. **77**, 2913 (1996)]. In our experiment atoms in a <sup>87</sup>Rb condensate are exposed to laser light which is tuned close to the transition frequency to an excited molecular state. By controlling the power and detuning of the laser beam we can change the atomic scattering length over a wide range. In view of laser-driven atomic losses we use Bragg spectroscopy as a fast method to measure the scattering length of the atoms.

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The great progress in the field of ultracold quantum gases in recent years can be largely attributed to the existence of magnetically tunable Feshbach resonances [1]. Since their first experimental introduction into the field [2, 3, 4] they have been widely used to arbitrarily tune the interactions between atoms. A plethora of experiments has been performed ranging for example from ultra-high resolution molecular spectroscopy [5] to the creation of bright matter wave solitons [6] as well as the production of new atomic [7] and molecular [8] Bose-Einstein condensates (BEC).

In general a Feshbach resonance occurs when a colliding pair of atoms is resonantly coupled to a molecular bound state. A magnetically tunable Feshbach resonance is based on Zeeman shifting a bound molecular state into resonance with the scattering state. Alternative coupling schemes for inducing Feshbach resonances have been proposed but never experimentally applied to control atomic interactions. The use of radiofrequency [9] and static electric fields [10] was suggested. Fedichev *et al.* [11] proposed optical coupling of the scattering state with the molecular state which was theoretically analyzed further in [12, 13]. This scheme, often referred to as “optical Feshbach resonance”, can be controlled via laser detuning and laser power.

Inducing Feshbach resonances with optical fields offers experimental advantages compared to magnetic fields. The intensity and detuning of optical fields can be rapidly changed. Furthermore complex spatial intensity distributions can be easily produced which result in corresponding scattering length patterns across the sample. Optical transitions are always available even when no magnetic Feshbach resonances exist. Recently Fatemi *et al.* [14] observed optical Feshbach resonances in photoassociation spectroscopy. They used photoionization to probe optically induced changes in the scattering wave function. However, the direct influence of the optical Feshbach resonance on the atomic scattering properties was not studied.

In this Letter we report a direct measurement of the atomic scattering length  $a$  in a BEC of <sup>87</sup>Rb ( $F = 1, m_F = -1$ ) as we cross an optical Feshbach resonance.

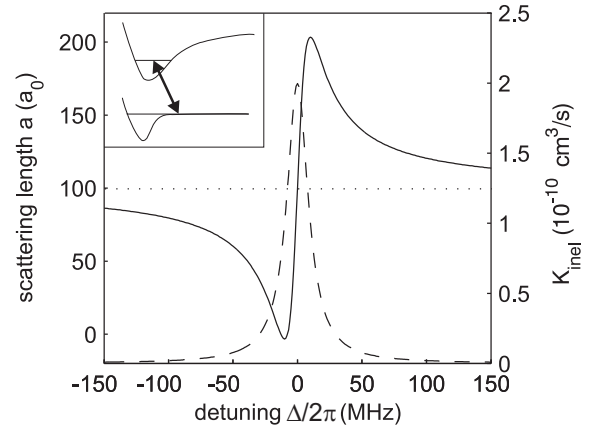


FIG. 1: Scattering length  $a$  (solid line) and inelastic collision rate coefficient  $K_{\text{inel}}$  (broken line) as a function of the laser detuning from the photoassociation resonance. The curves are based on Eqs. (1) and (2) for typical experimental parameters:  $\Gamma_{\text{stim}}/2\pi = 54$  kHz,  $\Gamma_{\text{spon}}/2\pi = 20$  MHz,  $k_i = 2.47 \times 10^5 \text{ m}^{-1}$ ,  $a_{\text{bg}} = 100 a_0$  (dotted line). Inset: Scheme for optically coupling the scattering state with an excited molecular state.

With moderate laser intensities of about  $500 \text{ W/cm}^2$  we can change the scattering length over one order of magnitude from  $10 a_0$  to  $190 a_0$  ( $a_0 = 1$  Bohr radius).

To optically modify the scattering length we use laser light tuned close to a photoassociation resonance which couples the continuum state of incoming free atoms to an excited molecular level (see inset in Fig. 1). This changes the wavefunction and consequently the scattering length of the scattering state. It also leads to atomic loss due to spontaneous decay via the molecular state. The resonant transition rate between the continuum state and the molecular state, which we denote  $\Gamma_{\text{stim}}$ , is proportional to the laser intensity. In our experiment  $\Gamma_{\text{stim}}/2\pi$  is on the order of a few 10 kHz. This is three orders of magnitude less than the spontaneous decay rate  $\Gamma_{\text{spon}}$  from the excited molecular state. In [12] Bohn and Julienne give convenient expressions for the scattering length  $a$  and the inelastic collision rate coefficient  $K_{\text{inel}}$  which

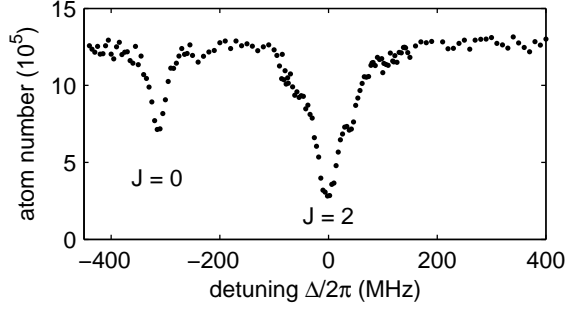


FIG. 2: Photoassociation spectrum of the excited molecular state used in the experiment. The two lines belong to the state  $|0_g^-(\sim S_{1/2} + P_{3/2}), \nu = 1\rangle$  and have rotational quantum numbers  $J = 0, 2$  respectively. Shown is the remaining atom number after exposing a BEC to a  $70 \mu\text{s}$  light pulse of  $460 \text{ W/cm}^2$  intensity. The detuning is given relative to the  $J = 2$  line. Each data point is an average of three measurements.

describes the photoassociation loss. For  $\Gamma_{\text{stim}} \ll \Gamma_{\text{spon}}$  these expressions can be approximated and, for a condensate [23], read:

$$a = a_{\text{bg}} + \frac{1}{2k_i} \frac{\Gamma_{\text{stim}} \Delta}{\Delta^2 + (\Gamma_{\text{spon}}/2)^2} \quad (1)$$

$$K_{\text{inel}} = \frac{2\pi\hbar}{m} \frac{1}{k_i} \frac{\Gamma_{\text{stim}} \Gamma_{\text{spon}}}{\Delta^2 + (\Gamma_{\text{spon}}/2)^2} \quad (2)$$

where  $a_{\text{bg}}$  is the scattering length in the absence of light,  $\Delta$  is the detuning from the photoassociation line,  $m$  the atomic mass and  $\hbar k_i$  the relative momentum of the collision. Fig. 1 shows  $a$  and  $K_{\text{inel}}$  as a function of the detuning  $\Delta$  for typical experimental parameters. According to Eqs. (1) and (2) one should in general choose large detuning and strong coupling in order to maximize the change in scattering length while keeping the losses low.

Our experiments are carried out with an almost pure  $^{87}\text{Rb}$  condensate in the  $|F = 1, m_F = -1\rangle$  spin state with typically  $1 \times 10^6$  atoms. The setup uses a magnetic transport scheme [15] to transfer atoms from a magneto-optical trap (MOT) chamber to a glass cell where the BEC is produced by rf-evaporation in a cigar shaped QUIC trap [16] with trap frequencies  $\omega_{\text{axial}}/2\pi = 15 \text{ Hz}$  and  $\omega_{\text{radial}}/2\pi = 150 \text{ Hz}$  [24]. The intensity stabilized photoassociation laser beam ( $\approx 40 \text{ mW}$ ) is derived from a Ti:Sa laser. It is aligned along the axial direction of the cigar shaped BEC and has a waist radius of  $76 \mu\text{m}$ . Its linear polarization is perpendicular to the trapping magnetic bias field of 2 Gauss. In our experiments we limit the maximum laser intensities to about  $500 \text{ W/cm}^2$  because we observe the appearance of a growing component of thermal atoms for higher intensities [25]. This effect is negligible for laser powers below  $500 \text{ W/cm}^2$ .

In order to identify a suitable molecular level with strong coupling to the continuum state we investigated molecular lines in the  $1_g$  and  $0_g^-$  potentials which connect to the  $(S_{1/2} + P_{3/2})$  and  $(S_{1/2} + P_{1/2})$  asymptotes. We choose the excited state  $|0_g^-(\sim S_{1/2} + P_{3/2}), \nu = 1, J = 2\rangle$

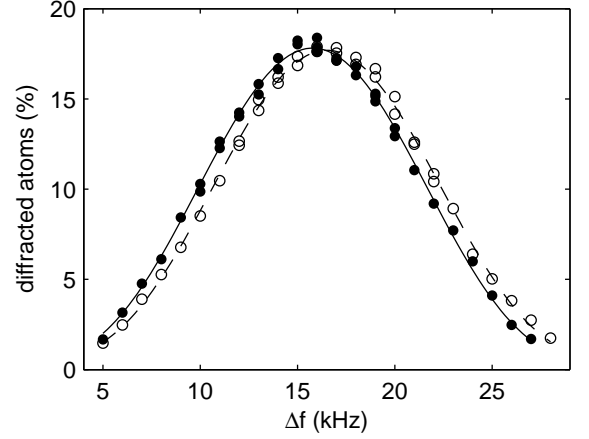


FIG. 3: Two Bragg resonance curves with an optically induced relative shift of  $0.75 \text{ kHz}$ . The percentage of the diffracted atoms is plotted against the frequency difference of the lattice beams. The two curves correspond to a detuning  $\Delta/2\pi = -47 \text{ MHz}$  (filled circles) and  $\Delta/2\pi = +47 \text{ MHz}$  (open circles) at a photoassociation laser intensity of  $460 \text{ W/cm}^2$ . The lines shown are fits to the data. For better comparison the right curve (open circles) has been scaled by a factor of 1.09 to the same height as the left one.

which is located  $26.8 \text{ cm}^{-1}$  below the  $D2$  line [17]. Fig. 2 shows the corresponding photoassociation line together with the line for  $J = 0$ . At a laser intensity of  $460 \text{ W/cm}^2$  the measured atom losses yield a peak inelastic collision rate  $K_{\text{inel}} = (2 \pm 1) \times 10^{-10} \text{ cm}^3/\text{s}$  which is a factor of 5 weaker than  $K_{\text{inel}}$  in the example of [12]. Losses due to excitation of the  $D2$  line can be neglected. We observe a strong intensity dependent light shift of  $215 \text{ MHz/(kW cm}^{-2})$  of the photoassociation line which might be mainly explained by coupling to a  $d$ -wave shape resonance [18].

Measuring the scattering length close to a photoassociation resonance requires a fast experimental method as atom losses restrict the observation time to below  $100 \mu\text{s}$  in our experiments. Thus the scattering length can neither be extracted from measurements of the collision rate [4] nor from the mean-field energy in a condensate expansion [2] both of which require a few ms. Instead we use Bragg spectroscopy [19] to determine the mean-field energy by imposing on the atoms a moving optical lattice composed of two counter-propagating laser beams with wavenumber  $k$  and an adjustable frequency difference  $\Delta f$ . The Bragg lattice transfers a momentum of  $2\hbar k$  to the atoms in a first order diffraction process. This is resonant when energy conservation is fulfilled, which for *noninteracting* atoms reads  $\hbar\Delta f_0 = (2\hbar k)^2/2m$ . For a condensate, however, the resonance frequency  $\Delta f_r$  is shifted by the mean-field energy. In the Thomas-Fermi approximation this yields a value of

$$\Delta f_r = \Delta f_0 + \frac{8\hbar}{7m} n_0 a \quad (3)$$

where  $n_0$  denotes the atomic peak density [19]. Observ-

ing this shift of the Bragg resonance frequency therefore allows to measure the product of density and scattering length.

We derive the two Bragg beams from a laser which is 1.4 nm blue detuned relative to the  $^{87}\text{Rb}$   $D2$  line. This determines  $\Delta f_0$  to be 15.14 kHz. Two acousto-optical modulators are used to control the frequency difference  $\Delta f$  between the two counter-propagating beams. The beams have a diameter of  $\approx 900 \mu\text{m}$  and are aligned along the radial trap axis in a horizontal direction. In our measurements we apply a  $70 \mu\text{s}$  square-pulse of Bragg light to the condensate. After 12 ms of time of flight, when the momentum components of the condensate have spatially separated, we use absorption imaging to measure the portion of condensate atoms that have been diffracted. We always choose the intensity of the lattice such that about 15% to 20% of the atoms are diffracted at resonance. Scanning  $\Delta f$  and determining the percentage of diffracted atoms yields curves as shown in Fig. 3 from which we extract the resonance positions. Shining in a photoassociation laser pulse ( $70 \mu\text{s}$  square pulse) at the same time as the Bragg pulse shifts the resonance position. This shift depends on the detuning  $\Delta$  from the molecular line (filled and open circles in Fig. 3).

For short illumination times  $T$  as in our experiment the shape of the spectra fits well to the Fourier transform of the rectangular light pulse,  $\sin^2(\pi(\Delta f - \Delta f_r)T)/(\Delta f - \Delta f_r)^2$ , which we use to fit the data (see Fig. 3). Our measurements show that in spite of the Fourier-limited width of the Bragg resonance of 13 kHz (FWHM) we can resolve the peak position to better than  $\pm 100$  Hz.

When we invert the frequency difference of the Bragg laser beams and diffract atoms to a momentum state with  $-2\hbar k$  instead of  $+2\hbar k$  we notice that the absolute value of the resonance frequency  $|\Delta f_r|$  changes. This can be explained by an initial condensate momentum of up to  $0.05 \hbar k$  which we find to slowly vary from day to day. This initial momentum is due to residual experimental imperfections like optical dipole forces of a slightly non-centered photoassociation beam. To eliminate this effect we always measure  $\Delta f_r$  for  $+2\hbar k$  as well as for  $-2\hbar k$  and then take the difference.

Figure 4 shows the data we obtain from scanning the photoassociation laser over the optical resonance for a fixed laser intensity of  $460 \text{ W/cm}^2$ . The number of atoms in the condensate at the end of the laser pulse is plotted in Fig. 4(a) indicating the position of the molecular line. On resonance about 90% of the atoms are lost after the  $70 \mu\text{s}$  of interaction time. Fig. 4(b) shows the resonance frequency  $\Delta f_r$  for Bragg diffraction as a function of laser detuning  $\Delta$ . For large positive (and negative) detuning  $\Delta$  the value of  $\Delta f_r$  agrees with the 16.6 kHz expected from theory for the background scattering length  $a_{\text{bg}} = 100 a_0$  [20, 21] and a BEC with  $\approx 8.2 \times 10^5$  atoms. As we tune across the molecular resonance the measured resonance frequencies exhibit a distorted dispersive shape. Following Eq. (3) this is the result of the combination of two effects: First the scattering length  $a$  varies with  $\Delta$  which

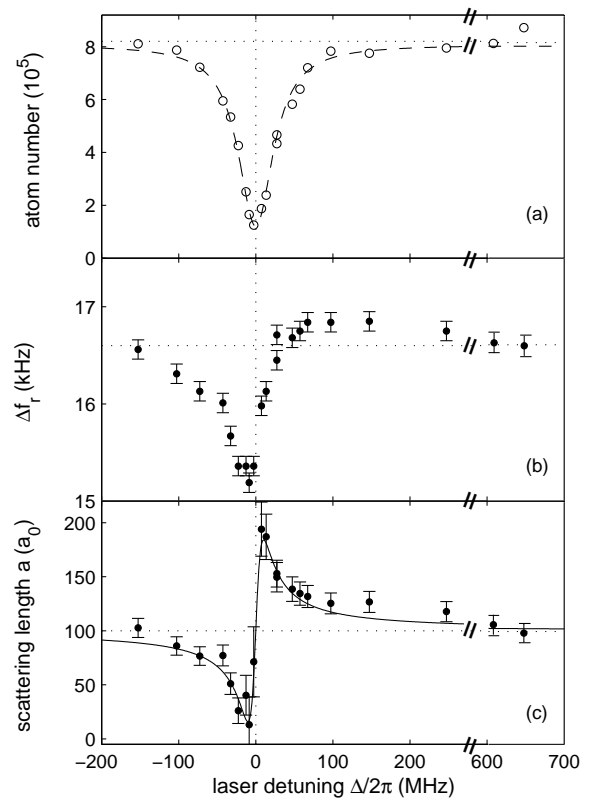


FIG. 4: Optical Feshbach resonance. In (a) the final atom number is plotted versus the detuning of the photoassociation laser (the dashed line is a Lorentz curve to guide the eye). The data in (b) displays the measured Bragg resonance frequencies. In (c) the values for the scattering length obtained from the data in (a) and (b) are plotted. The continuous line is a fit of Eq. (1) to the data.

alone should result in a dispersive line shape as in Fig. 1. Second the atomic density  $n_0$  decreases due to photoassociation losses which would, if the scattering length was constant, result in a symmetrical dip for  $\Delta f_r$ . On the right hand side of the resonance these two effects nearly compensate each other whereas on the left hand side the effects add up to produce a prominent dip in  $\Delta f_r$ .

In order to extract the scattering length  $a$  from the measured frequencies one can in a first approach replace the dynamically changing density  $n_0$  in Eq. (3) by a time averaged value  $\langle n_0 \rangle_t$ . The average  $\langle n_0 \rangle_t$  can be derived from the rate equation for the local density  $\dot{n} = -2K_{\text{inel}} n^2$  [22] describing two-atom losses. This yields values for  $a$  which differ only marginally from the ones in Fig. 4(c). The data in Fig. 4(c) were obtained from a more detailed examination which takes into account the full spatially resolved time evolution of the condensate density [26]. This includes the dynamical flattening of the condensate density profile caused by the rapid atom loss which is much faster than the trap frequencies [22]. Fig. 4(c) shows that with a laser power of  $460 \text{ W/cm}^2$  we can tune the scattering length over

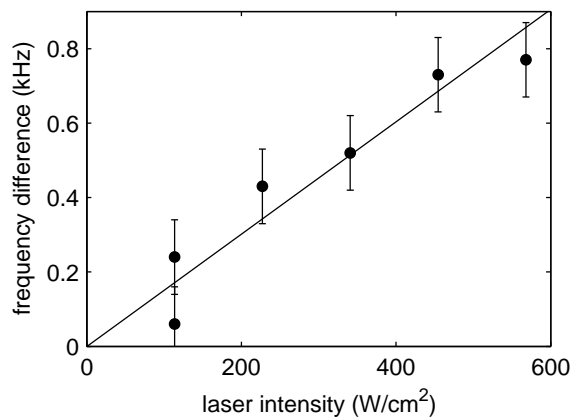


FIG. 5: Dependence of the optically induced mean-field shift on the laser intensity.

a range from  $10a_0$  to  $190a_0$ . A fit of Eq. (1) to these data for  $a$  yields a spontaneous decay width  $\Gamma_{\text{spon}}/2\pi$  of 20 MHz and a resonant inelastic collision rate coefficient  $K_{\text{inel}} = 1.7 \times 10^{-10} \text{ cm}^3/\text{s}$ . These values agree with those we obtain from atom loss measurements. Thus our data consistently confirm the intrinsic relation between  $a$  and  $K_{\text{inel}}$  as expressed in Eqs. (1) and (2).

The measured width  $\Gamma_{\text{spon}}/2\pi$  of 20 MHz is larger than the expected molecular decay width of 12 MHz (corresponding to two times the atomic width). This might be explained by the line width of the Ti:Sa laser of about 4 MHz and a power broadening of the line due to different light shifts of unresolved molecular hyperfine states [21, 22].

Fig. 5 demonstrates the linear dependence of the scattering length  $a$  on the photoassociation laser intensity.

For these measurements we determine the Bragg resonance frequency for the detunings  $\Delta/2\pi \approx \pm 50 \text{ MHz}$  at various photoassociation laser intensities. This is slightly complicated by the light shift and broadening of the photoassociation line which lead to an uncertainty in  $\Delta/2\pi$  of  $\pm 10 \text{ MHz}$ . We keep the final atom number and density fixed by adjusting the pulse duration for each laser intensity. This ensures that only changes in  $a$  are reflected in the varying mean-field shift. In Fig. 5 we plot the frequency difference  $\Delta f(+50 \text{ MHz}) - \Delta f(-50 \text{ MHz})$  which increases our signal.

In conclusion, our experiments demonstrate the tunability of the scattering length in ultracold samples by optically coupling free atoms to a bound molecular state. Because of the exquisite control one has over laser fields we expect optical Feshbach resonances to be valuable when it comes to control atom-atom interactions in demanding applications. The inherent losses suggest the use of high laser intensities at large detuning and a good choice of the molecular state in order to optimize the ratio of change in scattering length and loss rate. Optical Feshbach tuning could be particularly useful to control atomic interactions in optical lattices which are discussed as potential future quantum information processors.

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  - [23] For condensed atoms the collision rate coefficient is only half of the coefficient for thermal atoms as all atoms share the same quantum state.
  - [24] Details of our setup will be described elsewhere.
  - [25] We attribute this heating to the appearance of an uncontrolled corrugation in the photoassociation laser beam which transfers momentum components to the conden-

sate atoms. The corrugation could be a result of interfering backreflections from the glass cell windows.

[26] This calculation is a simulation of the Rabi flopping between two levels corresponding to the condensate com-

ponent at rest and the component with momentum  $2\hbar k$ . The changing density due to the loss is included by introducing a time dependent detuning.